

Can coronal hole spicules reach coronal temperatures?

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ABSTRACT

Aims. We aim with the present study to provide observational evidences on whether coronal hole spicules reach coronal temperatures.

Methods. We combine multi-instrument co-observations obtained with the SUMER/SoHO and with the EIS/SOT/XRT/Hinode.

Results. The analysed three large spicules were found to be comprised of numerous thin spicules which rise, rotate and descend simultaneously forming a bush-like feature. Their rotation resembles the untwisting of a large flux rope. They show velocities ranging from 50 to 250 km s⁻¹. We clearly associated the red- and blue-shifted emissions in transition region lines with rotating but also with rising and descending plasmas, respectively. Our main result is that these spicules although very large and dynamic, show no presence in spectral lines formed at temperatures above 300 000 K.

Conclusions. The present paper brings out the analysis of three Ca II H large spicules which are composed of numerous dynamic thin spicules but appear as macrospicules in EUV lower resolution images. We found no coronal counterpart of these and smaller spicules. We believe that the identification of phenomena which have very different origins as macrospicules is due to the interpretation of the transition region emission, and especially the He II emission, wherein both chromospheric large spicules and coronal X-ray jets are present. We suggest that the recent observation of spicules in the coronal AIA/SDO 171 Å and 211 Å channels is probably due to the existence of transition region emission there.

Key words. Sun: corona - Sun: transition region - Line: profiles - Methods: observational

1. Introduction

The term spicule refers to jet-like features expelled from the chromosphere as seen at the solar limb. They were first observed by Secchi (1877) and named spicules by Roberts (1945). Spicules are best viewed at the solar limb as bright features against the dark background of the solar corona in H α and Ca II images. Several studies report that these phenomena fall back along the same trajectory or fade out (Beckers 1972; Suematsu 1998). Many on-disk filament like features were identified as the counterpart of the limb spicules due to the similarities of their properties (Christopoulou et al. 2001; Rouppe van der Voort et al. 2007) and some were named ‘mottles’ (Tsiropoula & Schmieder 1997). Coronal hole spicules are found to be taller than quiet Sun spicules, probably due to the different configuration of the magnetic field of the two regions (Beckers 1972). Spicules/mottles have been observed in temperatures between 5 000 K and 300 000 K. However, De Pontieu et al. (2011) reported that a small but sufficient fraction of spicules, including coronal hole spicules are heated to temperatures above 1 MK based on observations from the Atmospheric Imaging Assembly (AIA) instrument onboard the Solar Dynamic Observatory (SDO) taken with the 171 Å filter. Transient events like spicules/mottles are of prime importance as they intermittently connect the chromosphere with the corona and possibly sustain the mass balance in the solar atmosphere (Tsiropoula & Tziotziou 2004). The down-flow observed in transition region lines was suggested to result from the mottle/spicule plasma returning to the solar surface (Tsiropoula & Tziotziou 2004; Pneuman & Kopp 1978; Withbroe 1983). If, however, all the material that is sent up through spicules/mottles is returned to the solar surface then

their contribution to coronal heating will be minimal, dismissing the possibility of spicules directly contributing to coronal heating (Withbroe 1983). Moreover, there are speculations that spicules/mottles maybe capable of transporting energy high into the upper chromosphere and even up to the corona (Pneuman & Kopp 1978; Athay & Holzer 1982) and, therefore, can be considered as possible candidates responsible for coronal heating (Athay 2000; De Pontieu et al. 2011).

Bohlin et al. (1975) revealed the existence of jet-like features found in images taken with the slitless NRL spectrograph during the Skylab mission. The events were named macrospicules as they resembled H α spicules, but were much larger and had longer lifetime. They appear increasingly inclined away from the pole as a function of increasing position angle measured from the pole which makes them comparable to H α spicules. They were first seen in He II 304 Å and only rarely in Ne VII 465 Å (5.7 K) (Bohlin et al. 1975). We would like to note here that the formation temperature of He II ranges from 5 to 12×10⁴ K with a maximum at 8×10⁴ K, corresponding to a low transition region temperature or the uppermost chromosphere (Jordan 1974). Due to the anomalous behaviour of the He I and II lines (Andretta et al. 2003), the presence of transient events in these lines does not directly tell where in the solar atmosphere these events originate. Therefore, to link features originating in the chromosphere such as spicules with phenomena seen at temperatures describing the transition region and corona is not a trivial task and strongly requires the use of suitable data.

Spectral and imaging macrospicule analysis were reported in several papers (Pike & Harrison 1997; Parenti et al. 2002; Pike & Mason 2002; Kamio et al. 2010). In SoHO/CDS data, they were registered in spectral lines with formation temperatures from 20 000 K to 1 MK (Pike & Harrison 1997), although Pike & Mason (2002) found no Mg IX (1 MK) emission

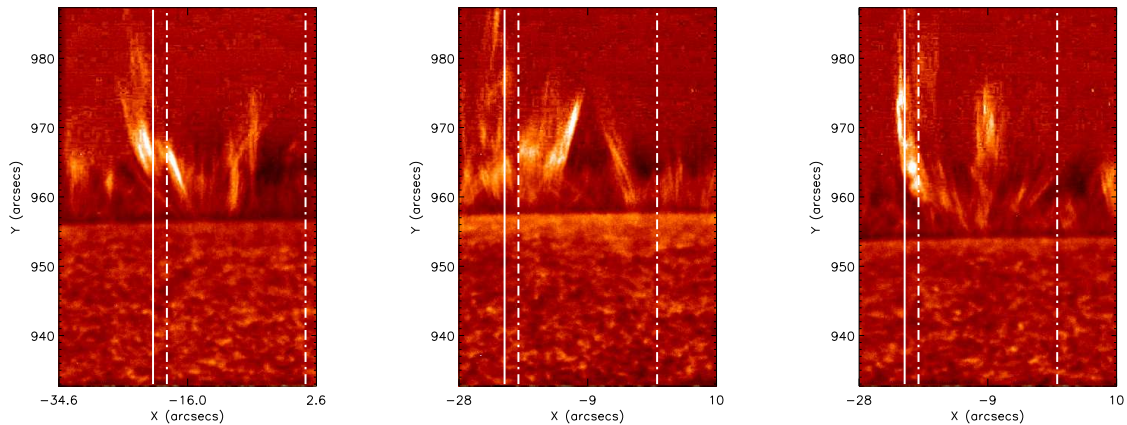


Fig. 1. SOT Ca II images showing spicules taken from left to right, on 2009, April 28 at 16:24 UT, on April 29 at 02:24 UT and 03:28 UT. The over-plotted solid line indicates the position of the SUMER slit, while the dashed-dotted lines indicate the EIS raster FOV.

in the region where macrospicules were detected in He I (20 000 K) and O V (250 000 K). Recently, Kamio et al. (2010) described a macrospicule seen in the He II 256 Å and Fe XII 195 Å (1.2 MK) lines from the Extreme-ultraviolet Imaging Spectrometer (EIS) onboard the Hinode satellite. The authors associated the macrospicule with an X-ray jet from a coronal bright point but no counterpart was reported in SOT Ca II H. Sterling et al. (2010) presented observations of an X-ray jet in X-ray telescope (XRT) images also seen in EIS 266'' slot images consisting of a blend of several lines including He II and Fe XV. The X-ray jet was associated with tall spicules seen in images from the Solar Optical Telescope (SOT) taken with the Ca II H filter and identified as type II spicules.

We performed specially planned multi-wavelength Hinode (EIS/SOT/XRT) and SoHO (Solar Measurements of Emitted Radiation (SUMER)) co-observations at the solar limb. The present paper describes the association of simultaneously evolving spicules seen in SOT Ca II with macrospicules judging from their appearance in SUMER and EIS observations. The aim of our investigation was to probe the possibility that spicules reach coronal temperatures, i.e. can deposit thermal energy directly in the solar corona. Sect. 2 describes the analysed data and their alignment. In Sect. 3 we give the obtained results. In Sect. 4 we discuss the open questions and state our conclusions.

2. Observations

The observations were taken at the North pole on 2009, April 28 and 29. The events were registered by the SOT, EIS and XRT onboard Hinode and the SUMER spectrometer onboard SoHO (Fig. 1). The SOT (Tsuneta et al. 2008) took observations with the Ca II H filter with a cadence of 10 s. The EIS (Culhane et al. 2007) observations were done with a 2'' slit and a 60 s exposure time. They consist of a large raster with a size of 70'' × 248'' followed by small rasters of 24'' × 248''. EIS took observations in many spectral lines, e.g. Fe VIII, Fe X, Fe XI up to Fe XXIII, O V and VI, and He II. We will discuss only the strongest ones, i.e. He II 256.32 Å (4.7 K) and Fe XII 195.12 Å (6.1 K). The XRT (Golub et al. 2007) was observing with the Al poly filter in a field-of-view (FOV) of 384'' × 384'' with a cadence of 30 sec. The SUMER spectrometer (Wilhelm et al. 1995) took a large raster followed by sit-and-stare observations using the 1'' × 300'' slit in O V 629.77 Å, N V 1238.82 Å, Mg X 624.90 Å and several other chromospheric lines (C I, Si II and S II). The O V 629 Å line

was used to obtain relative Doppler shift maps with the rest wavelength taken as an average from the whole dataset.

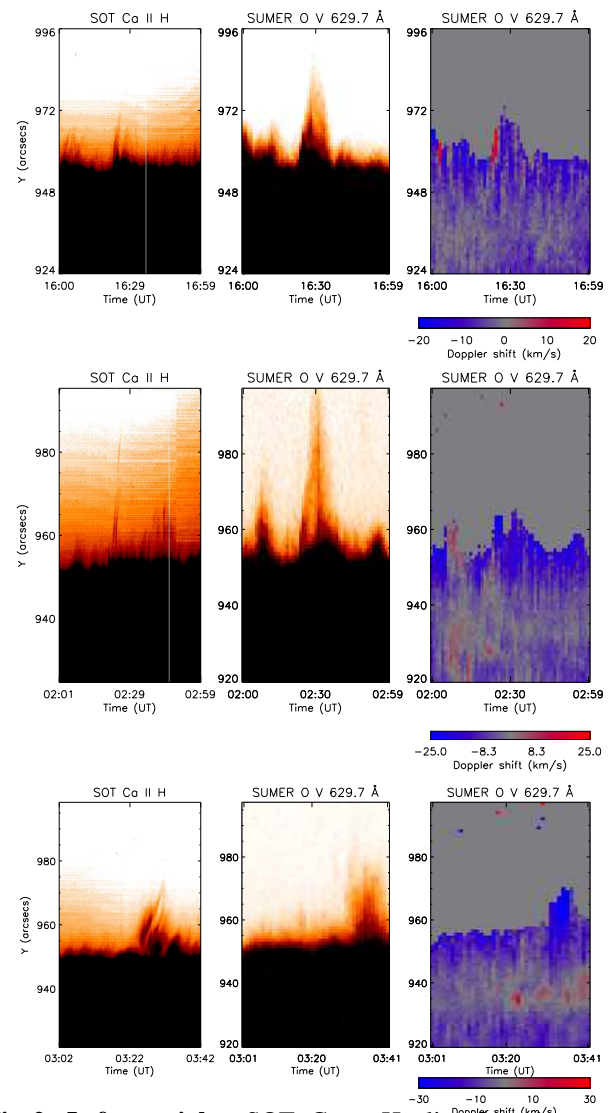


Fig. 2. Left to right: SOT Ca II H slice-time images, the corresponding SUMER sit-and-stare observations and Doppler velocity O V images on April 28 (top) and April 29 (middle and bottom).

Aligning data from various instruments was based on images obtained in spectral lines or filters with similar temperatures. First, a SUMER Mg x sit-and-stare image was aligned with a co-temporal slice-time image from XRT. Having done this, SUMER and SOT images were then aligned. Approximately nine pixels from an SOT image correspond to 1'' which is equivalent to the SUMER slit width. An automated procedure was written to cut a slice of 9 pixels in time from the SOT images and compare them with a SUMER sit-and-stare image in the Si II, N V and O V lines. Due to the uncertainties of the instrument pointing, it is necessary to search for the real position using an observed region of at least $\pm 20''$ from the commanded coordinates. We were satisfied with our alignment only when all off-limb features seen in the SUMER observations were identified with their SOT Ca II H counterpart. The EIS data were easily aligned with XRT using EIS images taken in high-temperature lines. The alignment was done (Fig. 1) with a precision of $\pm 2''$ to $\pm 4''$ which for the size of the observed events (more than $25''$ in Solar X) is in reasonable limits.

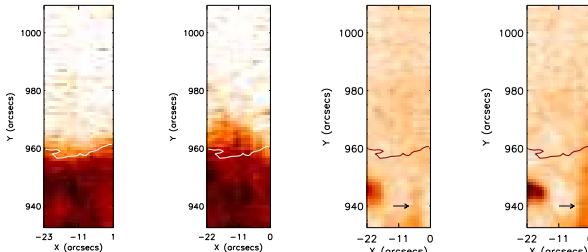


Fig. 3. EIS rasters taken on April 28 starting at 15:28 UT and 16:23 UT in the He II 256 Å line (first and second image) and the Fe XII 195 Å line (third and fourth image). The arrows indicate the X-ray jet from a coronal bright point identified from the XRT images.

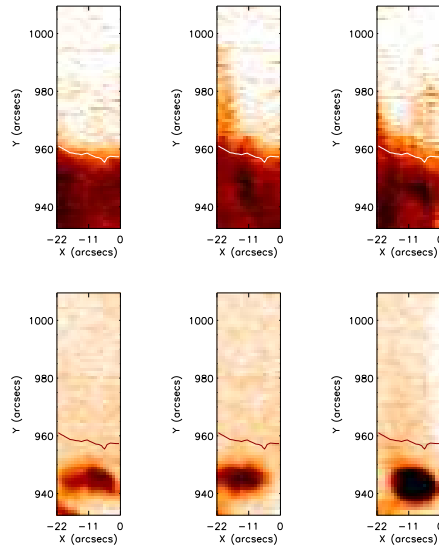


Fig. 4. EIS rasters taken on April 29 at 02:09 UT (left), 02:19 UT (middle) and 03:23 UT (right). The top and bottom row images were taken in the He II 256 Å and Fe XII 195 Å lines, respectively.

3. Results

The observed regions are seeded with thin dynamic jet-like events which correspond to the de Pontieu et al. (2007);

De Pontieu et al. (2011) type II spicules observed in coronal holes (see the online movies). After a very challenging but successful alignment of all instrument data, we selected for further analysis the three largest events which fall under the SUMER slit. They are comprised of numerous high velocity thin long spicules (termed type II spicules) which evolve simultaneously. The reason for analysing only the largest spicules is the lower spatial resolution of SUMER, EIS and XRT with respect to SOT (for more details see Sect. 2). The ratio of the spatial resolution of EIS ($2''$ slit width) to SOT ($0.1089''$), is approximately 18, which means that a feature identified in SOT has to be larger by more than twice the spatial resolution of EIS, i.e. more than $4''$ in width, in order to be identified in EIS data. In Fig. 1 we show the three spicules which represent ‘bushes’ of many thin spicules which rise simultaneously forming a large spicule (see the online movies). They reach various heights (in average more than 20 000 km) above the solar limb. Their bush-like horizontal expansion reaches up to 25 000 km. The proper motion of the spicules was estimated by following individual spicules in as many images as possible. We found a speed of rising between 50 and 250 km s⁻¹. The descending velocity was difficult to estimate because of the superposition of rotation, up and down-flows. We found a persistent blue-shifted emission of less than 50 km s⁻¹ even when rotation is not present which apparently corresponds to a down-flow.

The event on April 28 happened at around 16:25 UT and had a duration of 10 min in SOT Ca II. It was registered in SUMER O V 2 min later, i.e. 16:27 UT, and lasted around 12 min. The phenomenon can be described as multiple thin jets which are seen to shoot up at high speed. They rotate as one unit as they rise and finally disappear into the surroundings. The first event of April 29 took place at around 02:25 UT. The jet-like event rose almost from a blast and expended beyond the SOT FOV, i.e. more than 40 000 km above the solar limb. Just like the previous event, it also rotated and then disappeared. The third spicule rose quickly at around 03:21 UT and sustained its height, rotating for a period longer than the previously discussed events before it descended. Again, we observed a delay in the appearance of the event in the SUMER O V line. The duration of both events on April 29 is approximately 10 min.

We analysed the SUMER data taken in the chromospheric Si II 1250.41 Å blended with the C I 1250.42 and S II 1250.58 Å lines, the transition region O V 629.76 Å and N V 1238.82 Å lines, and the coronal Mg x 624.9 Å line. The spicules are clearly present in the chromospheric lines. In these lines as well as in transition region lines, the spicules appear as the so-called ‘macrospicules’, i.e. larger size with respect to the Ca II H spicules. In addition to the largest spicules discussed here, one can see several small size SUMER spicules which are also composed of several thin long SOT Ca II spicules. The features can be seen evolving under the SUMER slit in the edge enhanced image movies). In the transition region lines the spicules show strong blue- and red-shifted emission (Fig. 2 and the online movies). For the first time we were able to establish the meaning of the blue and red-shifted emission at this line-of-sight position. From the comparison of the simultaneously taken SUMER and SOT data (Fig. 2), we found that the Doppler shifts which were earlier interpreted by Cook et al. (1984); Pike & Harrison (1997) and Parenti et al. (2002) as rotating motions, do indeed mean a rotation, but they also mean an up-flow which corresponds to a red-shifted emission and a blue-shift which is consistent with down-flow. The blue-shift is persistent once the event took off. We should note that a single Gauss fit as presented in Fig. 2 does

not really give a full picture of the dynamics of these events. Only a careful analysis of individual pixels with sufficient signal provides the true evolution of the spicule plasmas.

The next step of our study was the analysis of spectral lines formed at coronal temperatures. No signal was detected in the coronal SUMER Mg x line for the duration of the large spicules. However, due to the uncertainties of using this line for coronal diagnostics (Madjarska 2011), we omit this observation from our conclusions. We concentrated our analysis on the behaviour of the EIS spectral lines which are perfectly suitable for coronal diagnostics. In order to identify the spicules in EIS data, we used the He II 256.32 Å line as reference. In Fig. 3 we present a raster taken at 15:28 UT (the last good raster before the large spicules took off) on April 28 with no visible off-limb features. By taking a limb contour in the He II 256 Å, we established our reference line which will represent the solar limb. The presence of the spicule in the He II raster image (the EIS FOV is shown in Fig. 1), is more than evident. The large spicule is also seen in the O V line, but the low signal in this line does not permit to show a representative image. The analysis of all iron lines from Fe VIII up to Fe XVI shows no evidence for the presence of a spicule at their corresponding formation temperatures. In Fig. 3 (third and fourth image), we give example raster images in the strongest line in the EIS spectrum, the Fe XII 195.12 Å line, before (third) and during (fourth) the course of the SUMER spicule. The jet-like features seen in the Fe XII raster images correspond to a X-ray jet from a bright point which is situated below the limb. This has been established by using an XRT animated sequence. The same is shown in Fig. 4 for the two events on April 29. Again, no trace of the large spicule is seen in the coronal lines.

4. Discussion and Conclusions

The present paper brings out the analysis of three large spicules named as macrospicules as seen in EUV spectral lines. The macrospicules appear to consist of many thread-like spicules as seen in high-resolution SOT Ca II H images which rise, rotate, descend and in general evolve almost simultaneously. We identified the counterpart of these large spicules in SUMER and EIS sit-and-stare and raster images, respectively. The large SOT spicules are very dynamic and appear as features which are usually identified as macrospicules in transition region emission lines. Our main result is that these spicules although very large and dynamic, show no presence in spectral lines formed at temperatures above 300 000 K. Macrospicules have been reported in coronal lines (Pike & Harrison 1997) and recently, a feature called macrospicule identified in the EIS He II line was clearly seen as an X-ray jet (Kamio et al. 2010). Where does the discrepancy between our results and these observations comes from? We strongly believe that the mis-identification or rather the identification of a different type of phenomena as macrospicules is due to the interpretation of the transition region emission and especially, the He I and II emission. Our recent multi-instrument analysis of a ‘classical’ X-ray jet clearly demonstrated that X-ray jets are strongly visible in the He II emission (Madjarska 2011). We believe that this is also the case of the event described by Kamio et al. (2010). Equally, spicules are prominent in these spectral lines. Forthcoming papers by Madjarska et al. (2011, in prep) and Subramanian et al. (2011, in prep) will give more information on this subject.

Recently, De Pontieu et al. (2011) reported the observation of spicules in the AIA/SDO 171 Å channel in active regions,

quiet Sun as well as in coronal holes (Fig. 3 in their paper and movies S8 and S9). This fact made us ask: Why do we not detect any coronal emission in EIS data of coronal hole spicules? It should be noted here that the two works (ours and the work of De Pontieu and co-authors) deal with different type of observations, spectroscopic and imaging. So, we decided to make a preliminary spectroscopic analysis of the AIA 171 Å channel. This channel will be dominated by Fe IX emission (<http://aia.lmsal.com/public/results.htm>). However, it also contains an abundance of cool Fe VIII, Ne V, O V and VI lines and therefore, when along the line-of-sight there is no emission from the Fe IX lines, the cooler lines will have a significant contribution. This was clearly demonstrated from simultaneous TRACE Fe IX/X 171 Å, and SUMER transition region and coronal observations (Madjarska & Doyle 2008, see Sect. 4). In order to make a preliminary analysis of the cooler emission contribution in the AIA 171, we checked co-observations of a large prominence by EIS and AIA. Solar prominences have very similar plasma parameters as spicules concerning temperatures and densities, but with the prominences being much larger, especially quiescent ones. Surprisingly, we identified clearly all solar prominences in the AIA 171 Å images. A check on the EIS observations for one of these prominences revealed an emission not higher than Fe VIII with a contribution function peaking at 400 000 K, i.e. at transition region temperature. Is it, therefore, possible that the spicules seen by De Pontieu et al. (2011) in the AIA 171 Å channel come from the emission of lower temperature lines? This question needs to be answered by careful spectroscopic studies of the response of the AIA channels.

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